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Comparison between solar utilization of a closed microalgae-based bio-loop and that of a stand-alone photovoltaic system

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Title: Comparison between solar utilization of a closed microalgae-based bio-loop and that of a stand-alone photovoltaic system

Article Type: SI: Bio/Chemicals from Algae

Keywords: microalgae; biomass; biogas; exergy; life cycle assessment

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Abstract: This study compared the solar energy utilization of a closed microalgae-based bio-loop for energy efficient production of biogas with fertilizer recovery against that of a stand-alone photovoltaic (PV) system. The comparison was made from the perspective of broad life cycle assessment, simultaneously taking exergy to be the functional unit. The results indicated that the bio-loop was more environmentally competitive than an equivalent stand-alone PV system, but had higher economic cost due to high energy consumption during the operational phase. To fix the problem, a patented, interior pressurization scheduling method was used to operate the bio-loop, with microalgae and aerobic bacterial placed together in the same reactor. As a result, the overall environmental impact and total investment were respectively reduced by more than 75% and 84%, a vast improvement on the bio-loop.

Dear Dr. Ashok Pandey,

Thank you for your letter and for the reviewers' comments concerning our manuscript titled "Comparison between solar utilization of a closed microalgae-based bio-loop and that of a stand-alone photovoltaic system" (ID: BITE-D-14-05008).

Please find enclosed our responses to the comments made by Reviewer #1 and Reviewer #2, along with the revised manuscript. We have considered carefully each comment and revised the manuscript according to the referees' helpful advice. Some further polishes have also made. The revised portion is highlighted in yellow in the attached version of the manuscript.

We greatly appreciate the suggestions made by the Editor and Reviewers, and believe this has led to a much improved manuscript.

I confirm that I am the corresponding author, and my address and other information is as follows:

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We look forward to hearing from you at your earliest convenience.

Yours sincerely,

Qiang Jin, Ph. D., Assoc. Prof.

Authors' response to reviewers' comments

Manuscript Number: BITE-D-14-05008

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Authors: Qiang Jin, Lei Chen, Aimin Li, Fuqiang Liu, Chao Long, Aidang Shan,

Alistair G.L. Borthwick

We thank the anonymous reviewers for thoroughly reading the manuscript and providing helpful comments and suggestions. In our response below, the text in italics provides the reviewers' comments, and the text in blue is our response.

Response to Reviewer #1

1. *Abstract: Delete 'Microalgae offer potentially high energy productivity per unit area, and so are an attractive sustainable energy option, helping alleviate fossil fuel dependency.'*

Done.

2. *Abstract: The lead author proposes' State the aim of the work first, then give main results.'*

We have modified the Abstract following the reviewer's comment.

The corresponding change is on page 2, lines 23-33.

3. *Abstract: Use past tense to describe the work done and results.*

Done.

4. *Do not use we, us, our in text.*

Done.

5. *Merge Sec 4 in results and discussion.*

As suggested, Section 4 has been merged with Section 3 and renamed “3.4 Further improvements”. Section 3 has been renamed “3. Results and discussion”.

The changes are to be found on page 19, line 402, and page 12, line 253.

6. *Remove Fig 4 by giving details in text only.*

Fig. 4 has been removed from the manuscript, since its message is effectively covered by the statement concerning symbiotic relationship (see page 20, lines 440-448).

7. *Several refs seem incomplete in the list.*

Thank you for pointing this out. We have re-edited the references with an appropriate style of complete information, and added one further reference in the revised manuscript that provides a more convincing introduction with more precise examples, as follow:

-Parmar, A., Singh, N.K., Pandey, A., Gnansounou, E., Madamwar, D. 2011.

Cyanobacteria and microalgae: A positive prospect for biofuels. *Bioresource Technology*, 102(22), 10163-10172

The corresponding addition is provided on page 4, line 69.

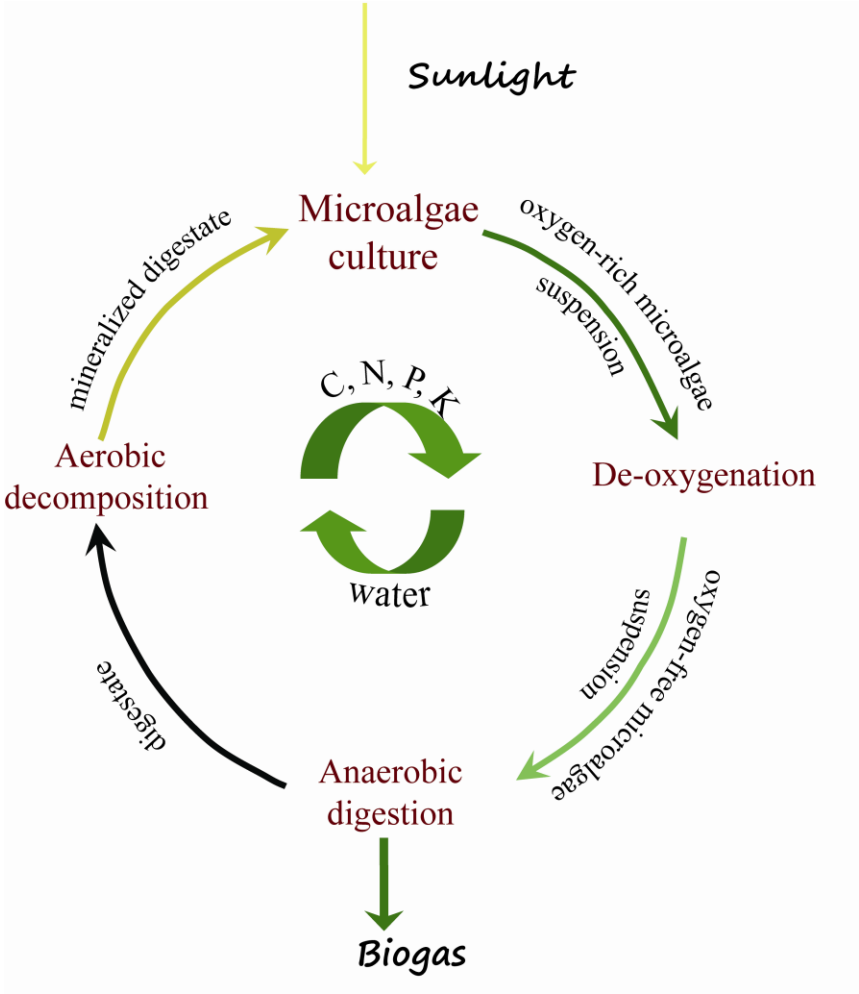
Response to Reviewer #2

1. *The authors may provide some core data in the abstract to avoid pure description.*

This is a very helpful suggestion. Core data on the final reduced environmental impacts and total investment relating to the improved bio-loop have been added to the Abstract on page 2, lines 32-33.

2. *The first "PV" in abstract should be "photovoltaic (PV)"*

The required change has been made (see page 2, line 25).



1. A closed microalgae-based bio-loop is assessed according to the broad LCA.
2. The bio-loop exhibits more competitive than the stand-alone PV system.
3. Operational energy consumption constitutes the main negative contributor.
4. The overall performances are significantly improved by pressurization and coupling.

**Comparison between solar utilization of a closed microalgae-based bio-loop
and that of a stand-alone photovoltaic system**

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Abstract This study compared the solar energy utilization of a closed microalgae-based bio-loop for energy efficient production of biogas with fertilizer recovery against that of a stand-alone photovoltaic (PV) system. The comparison was made from the perspective of broad life cycle assessment, simultaneously taking exergy to be the functional unit. The results indicated that the bio-loop was more environmentally competitive than an equivalent stand-alone PV system, but had higher economic cost due to high energy consumption during the operational phase. To fix the problem, a patented, interior pressurization scheduling method was used to operate the bio-loop, with microalgae and aerobic bacterial placed together in the same reactor. As a result, the overall environmental impact and total investment were respectively reduced by more than 75% and 84%, a vast improvement on the bio-loop.

Keywords: microalgae, biomass, biogas, exergy, life cycle assessment

1. Introduction

In the context of climate change and fossil fuel depletion, the promise of sustainable energy supply has generated tremendous interest in recent years. Renewable energy is expected to contribute significantly to mitigation of energy-related environmental impacts and reduction in national dependence on external energy supplies. Several competing technologies are under simultaneous development including solar energy, wind power, biomass, geothermal energy, hydropower, and tidal energy. Although superficially in completely different forms, solar energy and biomass energy derive directly from solar radiation and are preferred renewable energy sources owing to their availability and inexhaustibility.

Photovoltaic (PV) energy conversion involves the use of semiconductors to convert solar radiation into direct current electricity. A common misperception is that PV is an absolutely clean source of energy, without pollutant emissions during the operational phase (Stoppato, 2008). In fact, PV consumes a considerable amount of energy and emits GHG during the manufacturing of the solar cells, the assembly of PV modules, manufacture of balance-of-system (BOS) components, transport of materials, installation and retrofitting of PV systems, and their disposal or recycling (Kannan et al., 2006; Peng et al., 2013). Various toxic chemicals are associated with the manufacture of solar cells including silicon tetrachloride, hydrogen fluoride (HF) and heavy metals (As, Cr and Ni) (Fthenakis, 2003; Fthenakis & Kim, 2011).

Biomass comprises diverse organic matter that derives originally from green plants such as wood, crops and algae, which convert sunlight into biological material

1 through photosynthesis. Microalgae are attractive as a non-food biomass energy source
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3 that can produce 5 to 10 times more energy than other plant-based sources like corn
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5 and soy (Collet et al., 2011; Parmar et al., 2011). Once harvested, microalgae can be
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7 converted into various biofuels such as biodiesel, methane, ethanol, as well as butanol.
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9 However, life cycle assessment (LCA) and energy analyses (Clarens et al., 2010;
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11 Lardon et al., 2009), have found that the need for fertilizers, microalgae harvesting and
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13 dewatering lead to high energy debts and adverse environmental impacts that might
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15 render biofuel systems unviable. What is more, biodiesel from algae production leads
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17 to a negative energy balance because the dry and oil extraction processes account for
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19 more than 70% of total energy consumption (Lardon et al., 2009), and the yield of
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21 alcohols is too low to be commercially acceptable (John et al., 2011). Finally, it is often
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23 the case that some digestate discharges into watercourses, adding to the severe problem
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25 of eutrophication of lakes.
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28 To fix these problems, the lead author recently proposed a patented closed
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30 microalgae-based bio-loop (CN103290059A) to produce methane (Jin, 2013a). The
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32 system involved recycling through four steps of microalgae culture, de-oxygenation,
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34 anaerobic digestion and aerobic decomposition. The COD of microalgae suspension
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36 was much larger than the industrial design threshold value of 500 mg/L (Milieuhygiène
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38 & Foundation, 1989) , and so raw material could directly undertake anaerobic
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40 digestion without requiring energy-intensive concentration and dewatering steps. Phase
41
42 transition from microalgae to methane was employed in this process as an efficient
43
44 energy-conserving separation method that entirely bypassed the oil extraction step, and
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substantially reduced the energy debt and adverse environmental impacts mentioned above. This new process recovered not only the energy stored in biomass in a sustainable way, but also almost all the nutrients by completely recirculating and mineralizing the suspension of the digestate. The closed recirculation helped offset a significant fraction of the operating cost of the process and had negligible impact on eutrophication. Furthermore, a material transportation scheduling method controlled the new process (CN103290059A) (Jin, 2013b), relying solely on the interior biogas pressure energy of the system, rather than any external electricity. Further efficiency gains could be made by placing the microalgae and aerobic bacterial in the same reactor and exploiting their symbiotic relationship.

The goal of this paper is to assess the environmental, economic and social impacts of the closed microalgae-based bio-loop based on the methodological framework of broad LCA, and thence to compare the performance of the bio-loop against that of a stand-alone PV system for the same sunlight-originated energy input. Insight is provided into the relative merits and demerits of the closed microalgae-based bio-loop, and recommendations made on how to enhance the process.

2. Methodology

Life Cycle Assessment (LCA) is widely perceived as a standardized tool by which to assess a product or service system (ISO14040, 2009; ISO14044, 2006), with the focus restricted to the environmental impacts of the system. Recently, a broad LCA has emerged in response to the requirement for sustainability, adding the economic and social domains to conventional LCA. In the present study, the closed microalgae-based

bio-loop is analysed during the design stage using the broad LCA methodology to identify obstacles and limitations which require further specific research efforts to make the technology more sustainable.

2.1 Scope

The inventory was based on figures derived from academic resources, communications with industrial producers, and processes described in the Ecoinvent Databse. The closed microalgae-based bio-loop analyzed herein refers to a hypothetical system based on extrapolation from laboratory-scale studies, and combinations with known processes to design a realistic industrial facility. The bio-loop and stand-alone PV systems considered herein were both located in the south of China. Standard rules were used for replacement of infrastructure: the buildings had a 25-year lifespan, after which they were dismantled, with concrete sent ultimately to landfill, and steel-based, PVA, and EVA products recycled.

Figure 1 provides an overview of the closed microalgae-based bio-loop, which involved cycling through microalgae culture to biogas production. The photo-bioreactor cultivated the microalgae by photosynthesis. Microalgae suspension then entered the de-oxygenation plant, which progressively depleted the dissolved oxygen through respiration for strictly anaerobic process. Next, the oxygen-free suspension was injected into anaerobic digesters. The produced methane was of fuel quality and could be further converted into electricity, fuel cells, liquid fuel, etc. The entire digestate was then injected into an aerobic decomposition reactor to produce microalgae-available nutrients. Finally, the mineralized digestate was recirculated into

the photo-bioreactor, and the circulation process repeated. The daily flow values reported on figure 1 were determined for a facility designed for 12 m² of cultivated area; and 18.398 m³ of total effective volume for the digesters.

Schematically, the stand-alone PV system production process involved nine different unit operations, ranging from silicon extraction to the final panel assembling (Supplementary information, Figure S.1) (Fthenakis & Kim, 2011; Stoppato, 2008).

2.2 Functional unit

Microalgae energy can be transformed into other energy forms by diverse downstream processes, such as bioelectricity, heat and mechanical work (Clarens et al., 2010; Collet et al., 2011; Venkata Subhash et al., 2013). However, previous LCA studies have paid attention solely to the total quantity of the different forms of energy rather than the general energy quality when specifying the microalgae energy (Clarens et al., 2010; Collet et al., 2011; Lardon et al., 2009). In the present study, the considered functional unit was 1 MJ E_x based on the concept of exergy, which is a measure of potentially useful energy quality (Szargut, 2005; Szargut et al., 1988). The exergy outputs of the closed microalgae-based bio-loop and stand-alone PV systems were calculated using Eq. 1 and Eq. 2 respectively (Joshi et al., 2009; Szargut, 2005).

The molar chemical exergy of material is

$$E_{xch} = \Delta G_f + \sum_e n_e E_{xchne} \quad (\text{Eq. 1})$$

where ΔG_f is Gibbs free energy of formation of the compound, n_e is the amount of kmol of element e and E_{xchne} is the standard chemical exergy of the element e. The electrical exergy of the PV system is given by

$$E_{xelec} = E_{elec} - I' = V_{oc}I_{sc} - (V_{oc}I_{sc} - V_mI_m) = V_mI_m \quad (\text{Eq. 2})$$

Where E_{elec} represents the maximum electrical energy ($V_{oc}I_{sc}$), and I' denotes the electrical exergy destruction ($V_{oc}I_{sc} - V_mI_m$).

2.3 Inventory and detailed description of the closed microalgae-based bio-loop

2.3.1 Microalgae culture

Open raceways are not suitable for rapid cultivation of microalgae cultivation because of lower growth rate, poor controllability, water evaporation, and lack of resistance to outside intruders. In the present study, the microalgae culture was grown in a flat plate photo-bioreactor that relied on abundant sunlight and CO₂. The photo-bioreactor was manufactured from 3 mm thick polycarbonate (PC) sheet which was highly transparent to visible light and had good mechanical properties. The cultivation system comprised 60 photo-bioreactors, each of 0.2 m² (1 m long and 0.2 m wide) productive area and 3 cm depth. Water and nutrients were pumped into one side of the panels and microalgae were harvested on the other side via an overflow system.

The growth rate of microalgae was assumed to be 25 g m⁻² d⁻¹, corresponding to a daily productivity of 300 g d⁻¹. The microalgae concentration was 0.5 g L⁻¹. The quantities of CO₂ and original fertilizers for producing 1 kg of microalgae were determined by the elementary composition of microalgae as (C₁₀₆H₁₈₁N₁₅O₄₅P) (Redfield, 1958). Nitrogen, phosphorus and potassium were introduced via ammonium sulphate, single superphosphate and potassium chloride, respectively. CO₂ was bubbled into the photo-bioreactor by means of an air pump. Assuming the air pump had a capacity of 4.5 L air/min while consuming 5 watts, an air flow rate of 0.1 v/v/m would

consume a total energy of 0.0289 kWh of 1kg algae.

After aerobic decomposition, the suspension of digestate provided almost all the fertilizer and water requirements for the microalgae culture. The study assumed total efficiency in fertilizer use, so that there was no nutrient loss in the system. Annual evaporation resulted in water loss which was compensated by the freshwater.

2.3.2 De-oxygenation

Oxygen acts as an inhibitor in anaerobic digestion because of the presence of acetogens and methanogens which are strictly anaerobic. For microalgae suspension, the dissolved oxygen concentration has been found to range from 10 mg DOL⁻¹ in winter (115% of O₂ saturation) to 30 mg DOL⁻¹ in summer (375% of O₂ saturation) (Jiménez et al., 2003). Obviously, removal of the dissolved oxygen from the initially oxygen-rich microalgae suspension would be very conducive to the next stage of anaerobic digestion. Unfortunately, previous studies transferred the oxygen-rich initial microalgae suspension directly into the anaerobic digester, inevitably lowering the conversion efficiency (Collet et al., 2011). According to the present laboratory observations, the de-oxygenation process accorded with an endogenous respiration model under light-limited conditions without any addition of deoxidizer, and could rapidly generate an oxygen-free microalgae suspension provided the retention time lasted more than 2 hours. The de-oxygenation plant considered herein was designed for a hydraulic retention time (HRT) of 4 hours and a flow of 1.08225 m³ d⁻¹. On site, the plant would occupy a cube, of 0.8 m height, 1.2 m width and 1.2 m length.

2.3.3 Anaerobic digestion

Conventionally, feedstock entering an anaerobic digester includes large organic polymers and recalcitrant materials that result in the inert residues of the digestate. Owing to the absence of lignin and little cellulose, etc. (Williams & Laurens, 2010), microalgae exhibit a higher conversion efficiency than conventional feedstock, and achieve the full recycling of the digestate to create fertilizer for the microalgae culture, without the production of inert residues. Moreover, microalgae suspension can directly undergo anaerobic digestion, bypassing the energy-intensive concentration and dewatering steps, because the COD value of microalgae suspension is over 3 times higher than the COD threshold (500 mg/L) of anaerobic digestion (Milieuhygiène & Foundation, 1989).

Industrial data from state-of-the-art wastewater treatment plant were used to describe the behavior of the anaerobic digestion plant. Consequently, the anaerobic digester was designed for a hydraulic retention time (HRT) of 17 days, and total effective volume of 18.398 m³. Three cylindrical digesters were considered, each of 1.3 m height and 2.6 m internal diameter. The daily production of biogas was estimated to be 0.1124 m³·d⁻¹, and its composition was 70% CH₄ and 30% CO₂.

Microalgae-based anaerobic digestion involves a huge number of reactions and considerable heat generated by the bio-reactions (Appels et al., 2011). By including double thermal insulation, the bio-reaction heat was sufficient to offset the evaporation heat and the sensible heat that is carried away by the biogas, maintaining the plant at a temperature of around 20 to 45 °C (Wu, 2012).

2.3.4 Aerobic decomposition

Use of a digestate suspension to cultivate microalgae not only lowers the need for chemical fertilizers to promote microalgae production but also avoids eutrophication owing to N and P. In addition, the suspension can substantially reduce freshwater consumption during microalgae cultivation. Previous studies have focused on feeding the digestate directly back into the photo-bioreactor without pretreatment (Golueke & Oswald, 1959). The resulting nutrient recycling ratio was 50~80%(Brennan & Owende, 2010; Golueke & Oswald, 1959), because not all the nutrients in digestate were in bioavailable form. In order to achieve a more optimal recycling ratio, organic substance in the digestate had first to be converted to inorganic forms readily available to microalgae through aerobic bacteria mineralization. According to the present laboratory observations, almost all nutrients could be recycled after aerobic decomposition. Four cuboid reactors of 0.6 m height, 0.6 m width and 0.8 m length were considered. The energy cost of the air pump was 0.05175 kWh per day.

2.4 Stand-alone PV system inventory

A stand-alone photovoltaic (SAPV) array system of power rating 1 kWp was installed in Changshu city, Jiangsu Province, China. The photovoltaic modules were mounted on a fixed metal support structure. Each module was assumed to have a conversion efficiency of 16%. The PV array tilt angle was determined according to latitude, in order to maximize the incident solar intensity on the PV array and hence its power output. The PV array system consisted of five 200 Wp modules, each comprised of 54 polycrystalline silicon cells.

The life cycle of a polycrystalline silicon PV module commenced with extraction

of silica from quartz(Stoppato, 2008). The silica (SiO_2) was reduced to metallurgical-grade silicon (mg-Si) of 99.8% purity in an arc furnace at high temperature ($1800\sim 2000\text{ }^{\circ}\text{C}$), and then purified into solar-grade silicon (sog-Si) (99.9999%) through a “modified Siemens” process(Sherwani et al., 2010). The resulting high purity silicon was melted and casted into ingots of polycrystalline silicon, which were subsequently sliced into wafers using wire saws(Stoppato, 2008). The wafers were processed into solar cells by etching, texture, formation of an emitter layer, application of back surface layer and contacts, passivation and antireflective coating(Sherwani et al., 2010). The solar cells were tested, interconnected and subsequently encapsulated and framed into modules.

3. Results and discussion

3.1 Mass flows and energy consumption analysis

Table 1 summarizes the primary mass and energy flows generated during methane production from microalgae. Reinjection of mineralized digestate into the photo-bioreactor reduced the requirement for chemical fertilizers to almost zero because of the full closed-loop recycling process with negligible denitrification. The present laboratory observations indicated that the N, P and K mass balances in the closed microalgae-based bio-loop corresponded to recycling ratios of $99.8\pm 1.9\%$, $102.7\pm 1.1\%$ and $104.2\pm 0.9\%$, respectively, and hence almost no substances were released into the environmental rig, achieving a free supply of fertilizers and water. Benemann and Oswald’s proposed scheme had a nutrient recovery rate of 50%, implying a substantial operating cost, accounting for 6-8 cents per gallon of algal fuel

in 1987 U.S dollars (Benemann & Oswald, 1996). In microalgae cultivation, it is also desirable to recycle 99.97% of the water back to the culture because the addition of fresh water is a cost-prohibitive and often unsustainable option. For example, a hypothetical 12 m², 30 cm deep open pond with partial reflux would require 2.95×10⁻³ m³·d⁻¹ to compensate, a figure almost 26 times more than in the present study (1.134×10⁻⁴ m³·d⁻¹) at the same scale (Collet et al., 2011).

Mass and energy flows in the stand-alone PV system can be found in supplementary information (Supplementary information, Table S.1). In total, 50 wt% of the original high purity silicon input is lost in the cutting slurry of solar-grade silicon that seemingly represents a potential silicon feedstock source, but in fact has a recycling ratio of only 1~2% with purity of 90.8% (Wang et al., 2008). Many valuable materials are directly released from the stand-alone PV system, such as polyethylene glycol (28%), CaF₂ (100%) and argon gas (100%) (Stoppato, 2008). Photovoltaic cells also produce substantial quantities of wastewater, including rinsing water and concentrated acids (Drouiche et al., 2013), and the overall recycling ratio is only about 50~75% (Tsuo et al., 1998). For example, it has been established that 35% of the cell wafer cleaning solution must be compensated by fresh hydrofluoric (HF) acid solution (KULKARNI et al., 1994). The results highlight that the stand-alone PV system has a much lower material recycling rate than the closed microalgae-based bio-loop even if state-of-the-art technology is considered, such as “modified Siemens” process.

Cumulative energy demand (CED) is used as an indicator of energy requirements throughout the life cycle and is also considered as a good entry point into LCA. In the

present work, the corresponding analysis was performed, comparing the energy debt of a closed microalgae-based bio-loop to that of a stand-alone PV system. The results show that both systems achieved net positive energetic balance at two different levels, 0.0206 kWh/MJ Ex and 0.061 kWh/MJ Ex. The former value is three times lower than the latter in terms of energy balance performance.

3.2 Environmental assessment

In accordance with the International Organization for Standardization (ISO) 14040 framework, environmental impact assessments include three steps: characterization, normalization and weighting (ISO14040, 2009; ISO14044, 2006). In the present study, the selected impacts are: global warming potential (GWP) (kg CO₂ equivalent), eutrophication potential (EP) (kg PO₄⁻ equivalent), acidification potential (AP) (kg SO₂ equivalent), ozone layer depletion potential (ODP) (kg CFCs-11 equivalent) and photochemical oxidation potential (MIR).

To analyze the contribution of the closed microalgae-based bio-loop to each impact, the entire process chain was grouped into 4 categories:

- Production and use of energy by the facility;
- Extraction and production of fertilizers;
- Building and recycling of infrastructure;
- System output of the closed microalgae-based bio-loop.

Figure 2 shows the process contributions of the closed microalgae-based bio-loop to LCA environmental impacts within each category when producing 1MJ Ex. Energy consumption was the predominant impact, neglecting eutrophication. The proportion of

energy consumed **was** consistently more than 85%, with 100% for ozone layer depletion, 97 % for global warming potential, 93% for photochemical oxidation potential, and 86% for acidification potential. Building and recycling of infrastructure **contributed** almost 100% to eutrophication potential, due to the building of photo-bioreactors as well as their use; however, the corresponding value of 2.22×10^{-8} kg PO_4^- /MJ E_X **was** almost negligible. The high contribution **to global** warming potential caused by the system outputs of carbon dioxide and methane **was** mitigated by CH_4 combustion and CO_2 uptake for microalgae growth, achieving external circulation, which is **indicated** in Fig. 3 by the negative impact in the fertilizers category.

Figure 3 compares environmental impacts generated by producing 1 MJ E_X of the closed microalgae-based bio-loop and **the** stand-alone PV system. Each impact **was** standardized according to the value of the worst scenario specific to the impact. For both systems, neither substitution nor allocation **was** needed because there **was** no co-product produced during the operational phase. The results indicate that **the** stand-alone PV system **was** the worse option in terms of acidification depletion, global warming potential, eutrophication, and ozone layer depletion. The eutrophication potential based on the stand-alone PV system **was** 315 times higher than the closed microalgae-based bio-loop. The latter **achieved** completely internal circulation, leading to almost no direct emission **to** the environment; the former **consumed a** considerable amount of energy and **emitted** chemical substances from the solar cell itself **during** production, including nitrogen oxide, phosphate and nitrate. If directly discharged into

soil or a river instead of being recycled, the digestate would lead to a thousand-fold increase in eutrophication potential for the closed microalgae-based bio-loop over the stand-alone PV system. With regard to ozone layer depletion, the stand-alone PV system had an impact roughly 2300 times higher than that of the closed microalgae-based bio-loop, principally because a considerable amount of silicon tetrachloride (SiCl_4) was used in the “modified Siemens” process and a large amount of energy was consumed in the transformation of metallic- into solar-silicon. The life cycle acidification depletion of the stand-alone PV system was 3.45 times higher than that of the closed microalgae-based bio-loop due to considerable direct emission of SO_2 , except for the influence of energy consumption, which dominated the contributions for the entire stand-alone system. The greenhouse gas emission of the stand-alone PV system was 1.56 times that of the closed microalgae-based bio-loop, mainly due to energy consumption during transformation of metallic silicon into solar silicon and substantial direct emission of CO_2 during the metallic silicon production phase. The stand-alone PV system performed better than the closed microalgae-based bio-loop solely in terms of photochemical oxidation potential, noting that the photochemical oxidation potentials of both systems were primarily related to electricity consumption.

Obviously, the closed microalgae-based bio-loop does offer advantages over the stand-alone PV system regarding environmental impact, whereas the former involves higher energy consumption than the latter during the whole life cycle. The primary reason for this unexpected result was that the closed microalgae-based bio-loop

simultaneously achieved internal and external circulations, but the stand-alone PV system led to increased direct emissions into the environment.

3.3 Economic and social assessment

Table 2 provides an overview of the capital and operational costs of the full microalgae-based bio-loop and standalone PV system, based on academic expert advice, communications with industrial producers, and the Ecoinvent database. The closed microalgae-based bio-loop performed internal and external recirculations to mitigate fresh CO₂ and fertilizer demands, leading to a decrease in cost of fertilizer from 0.012 \$ kg⁻¹algae a⁻¹ to 0 \$ kg⁻¹algae a⁻¹ (25g algae m⁻² d⁻¹ productivity), accounting for 30% of the microalgae culture costs. Freshwater compensation was almost negligible (0.005661 \$.y⁻¹) compared to the overall operational cost (40.9136 \$.y⁻¹). It appears that the operational cost of the closed microalgae-based bio-loop depended mainly on energy consumption, which took up 82.6% of total investment. Therefore, the closed microalgae-based bio-loop could be significantly improved by establishing a novel low-cost operational method.

The manufacturing processes involved in the closed microalgae-based bio-loop were relatively simple, involving certain widely available materials, such as glass, plexiglass and polycarbonate. The capital cost of a stand-alone PV system was higher than a closed microalgae-based bio-loop, owing to the more complicated technology involved (including the use of more than 20 different kinds of material), the use of expensive semiconductors, the additional cost of processing materials into useable solar cells, and the greater expense incurred in the training and education of employees

(Stoppato, 2008). On the other hand, the operational cost of the closed microalgae-based bio-loop was 16.4 times higher than the stand-alone PV system, because the latter consumed no energy during operation. Overall, the total investment per MJ E_x of the closed microalgae-based bio-loop was approximately 10 times as much as the stand-alone PV system.

Both technologies have positive and negative long-term effects on the local community. Although there is presently a lack of knowledge about the social impacts of the closed microalgae-based bio-loop and stand-alone PV system, qualitative analyses of both systems can nevertheless be carried out. The closed microalgae-based bio-loop and stand-alone PV system can mitigate increasing energy demand, especially in remote areas, thereby making significant contributions to rural income and employment. The closed microalgae-based bio-loop has more commercial potential than the stand-alone PV system thanks to its lower capital cost, particularly in undeveloped and developing countries. The closed microalgae-based bio-loop poses almost no toxic exposure risk to workers and local communities during its entire life cycle. By contrast, the stand-alone PV system utilises certain harmful chemicals such as arsine, phosphine, HF, $POCl_3$, which could have potential adverse impacts on the health of workers and local communities through incorrect operation and accidental spills during manufacture(Fthenakis, 2003; Fthenakis & Kim, 2011). For example, during the processing of solar cells, any leakage causing human exposure to arsine at concentration above 6 ppm would result in irreversible health effects, such as acute renal failure(O'Neivl, 2013).On contact with moist atmosphere, silicon tetrachloride

(encountered during the polycrystalline silicon production) reduces to silica acid and hydrogen chloride which are strong irritants to the skin, eyes, and respiratory system (Kapias et al., 2001). Furthermore, accidental spills could lead to public alarm. Health and safety concerns include the threats of hazardous gas leaks and potential explosions at the manufacturing facility.

3.4 Further improvements

It should be emphasized that no closed microalgae-based bio-loop has been installed at industrial-scale at the time of writing. However, the present paper has used reasonable assumptions and currently available technologies to propose an efficient microalgae-based bio-loop, whose design and performance could be further enhanced in the future. The main objective of the present study is to identify the main bottlenecks in the process and provide preliminary information for decision-makers to begin determining the most environmentally, economically and socially efficient production route.

Turning to the total energy costs of the closed microalgae-based bio-loop, it should be noted that 90% of the process energy consumption occurred in the operational phase, and this could be jeopardized in practice, ending up with a counter-productive production chain. Analysis of the distribution of environmental impacts and economic investment in comparison with the stand-alone PV system also highlighted that energy consumption during the operational phase was the major bottleneck regarding the environmental impacts and commercialization of microalgae-based biogas production. Better control of energy consumption would not

only improve the energy balance but also significantly decrease a wide range of adverse impacts (abiotic depletion, ozone depletion, acidification and global warming potential), thus enhancing the overall environmental and economic performances.

The lead author has developed and patented a material transportation scheduling method for the operational phase (CN103232938 A) (Jin, 2013b), which relies only on the interior biogas pressure energy of the system, rather than any external electricity. Moreover, since CO₂ dissolves much more readily in water than CH₄ at higher pressure, the biogas quality is also deeply affected so that CH₄ tends to dominate (Zhao et al., 2010). Accordingly, pressurization, biogas production and purification can be integrated in a single system, thereby drastically reducing the environmental impacts and economic expenses incurred by these three processes. Figure 4 illustrates the reduced impacts and expenses of the closed microalgae-based bio-loop with pressurization (Scenario 2) compared to the previous electricity scheduling method (Scenario 1). As observed, the life cycles GWP, AP, MIR and ODP of Scenario 2 decreased significantly by 86.6%, 76.6%, 83% and 89.23% respectively. Eutrophication in the life cycle of Scenario 2 decreased by a mere 0.027%; this was due mainly to the manufacture of polycarbonate (PC) sheet instead of electricity consumption. The operational cost of Scenario 2 reduced from 40.91 \$/yr to 7.88 \$/yr, respectively, accounting for about 74% of the total investment.

The closed microalgae-based bio-loop involved a completely independent micro-ecosystem, comprising a cycle chain of producers, consumers and decomposers (microalgae, anaerobic bacteria and aerobic bacteria). Further analysis of this

micro-ecosystem shows that microalgae not only use the decomposition products of aerobic bacteria as fertilizers but also have a symbiotic relationship with them. More precisely, microalgae produce the O₂ necessary for aerobic bacteria to mineralize organic matter, consuming in turn the CO₂ released from aerobic bacteria respiration. Both the microalgae and the aerobic bacteria exhibit a high degree of uniformity in the survival environment. Therefore, microalgae culture and aerobic decomposition can be coupled in the same reactor, encouraging smoother exchange of CO₂ and O₂ and providing a mechanism for efficient mixing. Figure 4 compares the impacts and expenses of the closed microalgae-based bio-loop (Scenario 1) with those of a coupled reactor (Scenario 3). The results indicate that the impacts caused by use of an air pump and polycarbonate (PC) sheet generally decreased by at least 10%, reaching over 76% in the case of eutrophication. The capital and operational costs each decreased roughly by 9%, and the corresponding total investment varied from 1120 \$ to 1012 \$.

If the pressurization and coupled reactor technology were to be simultaneously integrated into a closed microalgae-based bio-loop (Scenario 4), the overall environmental performance would improve substantially for less capital expenditure. The results show that most of the environmental impacts of Scenario 4 fell well below 15% of those of Scenario 1 (Fig. 4). Eutrophication decreased by almost 76.4%. The operational and capital costs of Scenario 4 decreased by about 91% and 18% respectively, and the associated total investment ranged from 1120 \$ to 177 \$.

Integration of pressurization with the coupled reactor should make the closed microalgae-based bio-loop more environmentally beneficial than the stand-alone PV

system. The adverse environmental impacts of the stand-alone PV system were all more than 9 times more severe than those of Scenario 4. The photochemical oxidation potential of the stand-alone PV system was roughly 4.5 times higher than that of the closed microalgae-based bio-loop. The operational cost of Scenario 4, previously the main bottleneck of the closed microalgae-based bio-loop, decreased substantially from 16.4 to 1.6 times that of the stand-alone PV system.

5. Conclusions

For the current state-of-the-art technology, the stand-alone PV system appears to have lower potential than the closed microalgae-based bio-loop in mitigating energy-related environmental burden. The study found that the main barrier to implementation of the bio-loop was its considerable energy consumption during the operational phase, which in turn constituted the main contributor to environmental impacts and total investment. In fact, significant improvements in pressurization material scheduling and coupled reactor design could lead to the bio-loop producing more environmentally and commercially viable biogas.

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Figure captions

Figure 1 Schematic diagram of closed microalgae-based bio-loop

Figure 2 Process contributions to the production of 1MJ E_x for closed

microalgae-based bio-loop. The abbreviations GWP, EP, AP, MIR, ODP refer to global warming potential, eutrophication potential, acidification potential, ozone layer depletion potential, and photochemical oxidation potential.

Fig. 3. Comparison of impacts generated by production of 1MJ E_x for closed microalgae-based bio-loop and stand-alone PV system. The abbreviations GWP, EP, AP, MIR, ODP refer to global warming potential, eutrophication potential, acidification potential, ozone layer depletion potential, and photochemical oxidation potential.

Fig. 4. Impacts of modified closed microalgae-based bio-loop. Scenarios 1 to 4 refer to the following: closed microalgae-based bio-loop with electricity scheduling method; closed microalgae-based bio-loop with pressurization; closed microalgae-based bio-loop with a coupled reactor; and closed microalgae-based bio-loop with pressurization and a coupled reactor. The abbreviations GWP, EP, AP, MIR, ODP refer to global warming potential, eutrophication potential, acidification potential, ozone layer depletion potential, and photochemical oxidation potential.

Table 1 Mass and energy flows generated by the production of 1kg of microalgae

Type	Description	Quantity	Units
Operation 1: microalgae culture			
Output	Flowout of the photo-bioreactor	3.608	m ³ /kg algae
Input	Mineralized digestate	3.608	m ³ /kg algae
Input	Electricity consumption(air pump)	0.0289	kWh/kg algae
Input	N	0	kg/kg algae
Input	P	0	kg/kg algae
Input	K	0	kg/kg algae
Input	Water	0.3779	kg/kg algae
Operation 2: de-oxygenation			
Output	Flowout of the de-oxygenation plant	3.608	m ³ /kg algae
Input	Flowout of the photo-bioreactor	3.608	m ³ /kg algae
Input	Electricity consumption (peristaltic pump)	0.1534	kWh/kg algae
Operation 3: anaerobic digestion			
Output	Biogas(70% CH ₄)	0.375	m ³ /kg algae
Output	Digestate	3.608	m ³ /kg algae
Input	Electricity consumption (peristaltic pump)	0.1534	kWh/kg algae
Input	Flow out of the de-oxygenation plant	3.608	m ³ /kg algae
Operation 4: aerobic decomposition			
Output	Mineralized digestate	3.608	m ³ /kg algae
Input	Electricity consumption (air pump)	0.0289	kWh/kg algae

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Input	Digestate	3.608	m ³ /kg algae
Input	Electricity consumption (peristaltic pump)	0.1725	kWh/kg algae

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1	619	Table 2 Capital and operational costs of the closed microalgae-based bio-loop and				
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4	620	stand-alone PV system				
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6		Closed microalgae-based				
7			Stand-alone PV system	Sources and assumptions		
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9		bio-loop				
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11		Capital and installation costs				
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13						
14		Photo-bioreactor	45.3403 \$	-		
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17		De-oxygenation plant	2.5216 \$	-		
18						
19						
20		Anaerobic digestion plant	31.51 \$	-		
21						
22						
23		Aerobic decomposition		25 years lifetime		
24			3.0739 \$	-		
25		reactor				
26						
27						
28		Pump	15.0494 \$	-		
29						
30		Total capital cost	97.4952 \$	6243.75 \$		
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33		Operational cost				
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35						
36		Electrical supply	37.008 \$/yr	0 \$/yr		
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39		Water supply	0.005661 \$/yr	0 \$/yr		
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42		Fertilizer supply	0 \$/yr	0 \$/yr		
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44		Maintenance	3.9 \$/yr	249.75 \$/yr		
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47		Total operation cost	40.9136 \$/yr	249.75 \$/yr		
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50		Total cost of ownership	1120.3352 \$	12487.5 \$		
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53		Cost of 1 MJ E _x	0.6458 \$/MJ E _x	0.07176 \$/MJ E _x		
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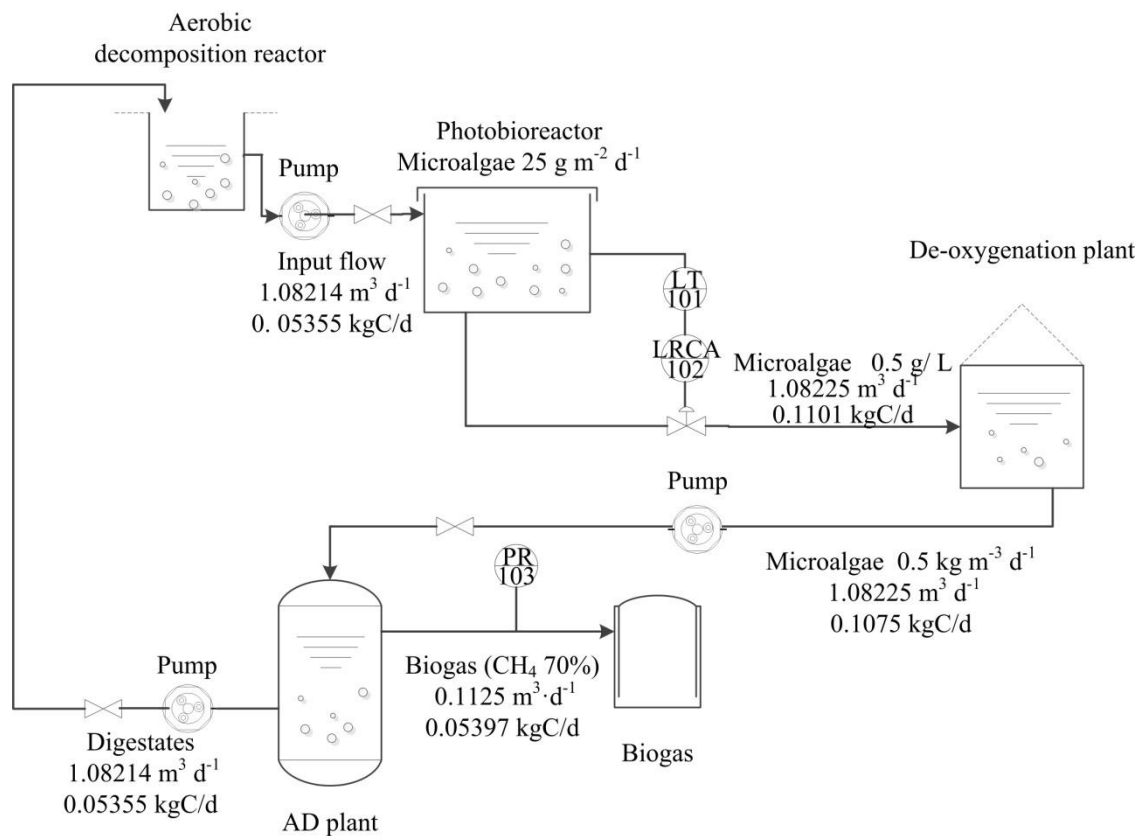


Fig. 1. Schematic diagram of closed microalgae-based bio-loop

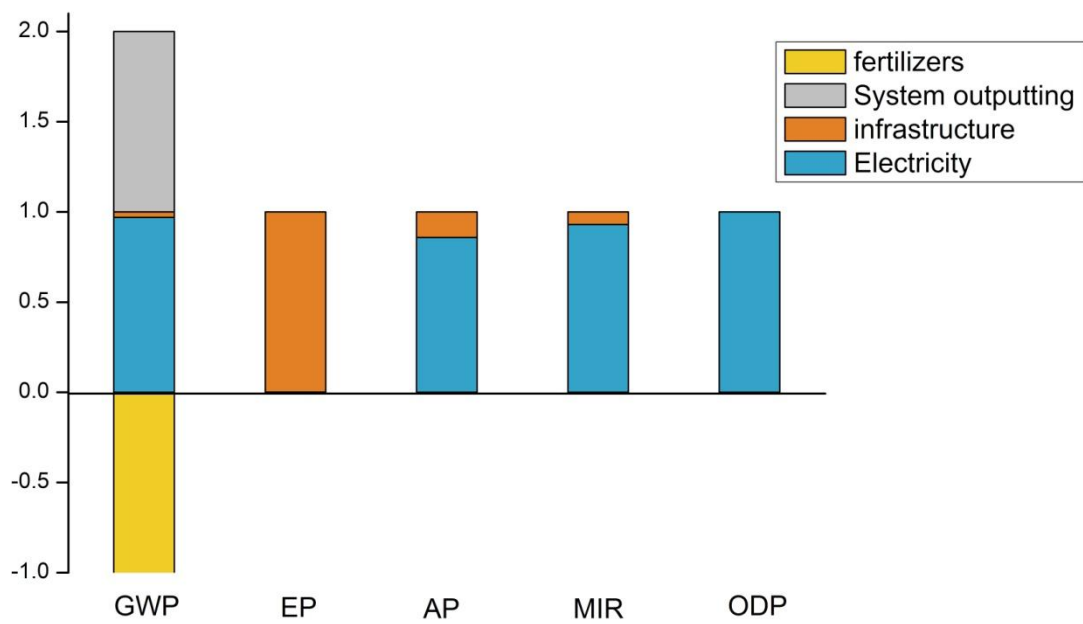


Fig. 2. Process contributions to the production of 1MJ E_x for closed microalgae-based bio-loop. The abbreviations GWP, EP, AP, MIR, ODP refer to global warming potential, eutrophication potential, acidification potential, ozone layer depletion potential, and photochemical oxidation potential.

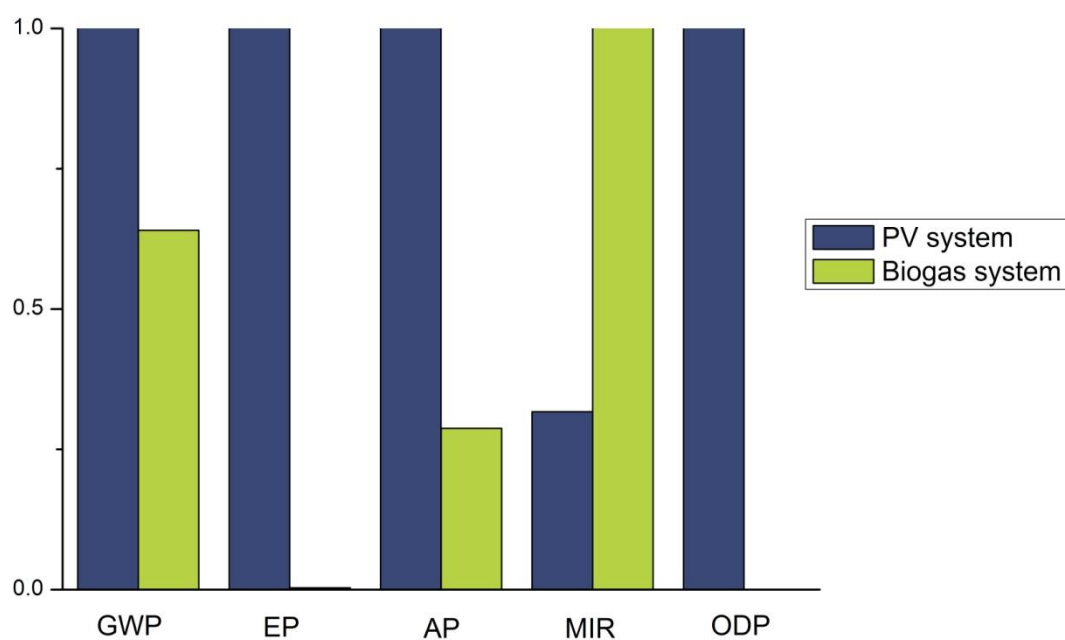


Fig. 3. Comparison of impacts generated by production of 1MJ E_x for closed microalgae-based bio-loop and stand-alone PV system. The abbreviations GWP, EP, AP, MIR, ODP refer to global warming potential, eutrophication potential, acidification potential, ozone layer depletion potential, and photochemical oxidation potential.

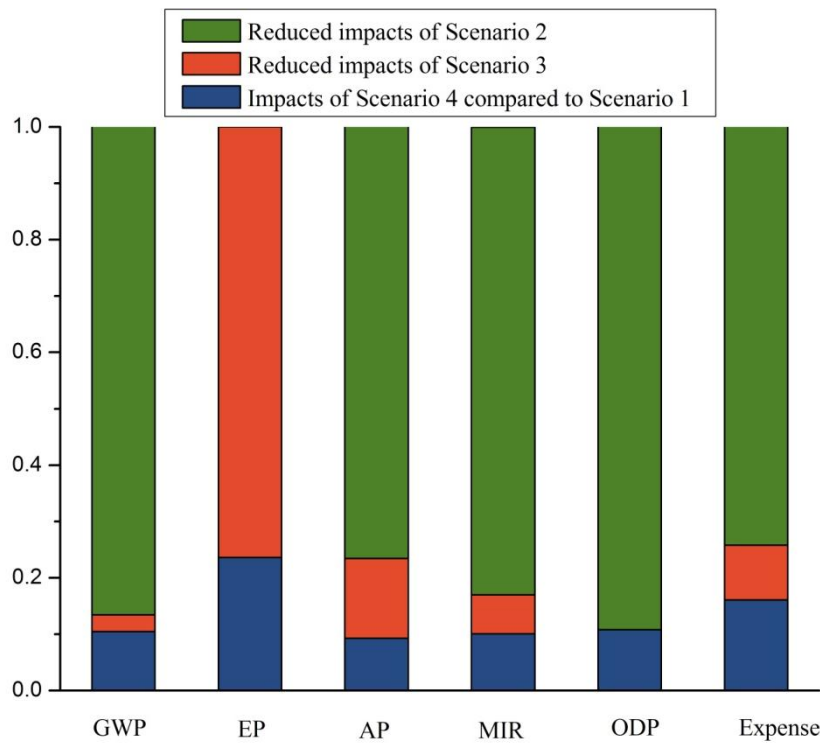


Fig. 4. Impacts of modified closed microalgae-based bio-loop. Scenarios 1 to 4

refer to the following: closed microalgae-based bio-loop with electricity scheduling method; closed microalgae-based bio-loop with pressurization; closed microalgae-based bio-loop with a coupled reactor; and closed microalgae-based bio-loop with pressurization and a coupled reactor. The abbreviations GWP, EP, AP, MIR, ODP refer to global warming potential, eutrophication potential, acidification potential, ozone layer depletion potential, and photochemical oxidation potential.

Electronic Annex

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